

EFFECT OF VECTOR MESON MASS DECREASE ON SUPERFLUIDITY IN NUCLEAR MATTER

TOMONORI TANIGAWA

*Department of Physics, Kyushu University,
Fukuoka 812-8581, Japan
E-mail: tomo2scp@mbox.nc.kyushu-u.ac.jp*

MASAYUKI MATSUZAKI

*Department of Physics, Fukuoka University of Education,
Munakata, Fukuoka 811-4192, Japan
E-mail: matsuza@fukuoka-edu.ac.jp*

1S_0 pairing in nuclear matter is investigated by taking the hadron mass decrease into account via the “In-Medium Bonn potential” which was recently proposed by Rapp *et al.* The resulting gap is significantly reduced in comparison with the one obtained with the original Bonn-B potential and we ascertain that the meson mass decrease is mainly responsible for this reduction.

Superfluidity in nuclear matter is one of the important issues in nuclear physics since it forms the foundation for nuclear structure theory and has close relationship to neutron-star physics. To describe a nuclear many-body system, relativistic models are attracting attention as well as non-relativistic ones. This is due to the success of Quantum Hadrodynamics (QHD) originated with the study by Chin and Walecka in 1970’s.¹

We studied 1S_0 pairing in nuclear matter by means of QHD, which has been succeeded in describing the various phenomena of nuclei, that is, not only the saturation property of nuclear matter, but spherical, deformed and rotating nuclei. Therefore improvement on the description of pairing which is essential in open shell nuclei would make QHD more reliable. To speak of neutron-star physics, relativistic effect might be important due to high density which is a few times larger than the normal nuclear matter density.

As is well known, QHD is an effective field theory of hadronic degrees of freedom. The Lagrangian density for the present model is like this:

$$\begin{aligned} \mathcal{L} = & \bar{\psi}(i\gamma_\mu\partial^\mu - M)\psi + \frac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma) - \frac{1}{2}m_\sigma^2\sigma^2 \\ & - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\mathbf{R}_{\mu\nu}\cdot\mathbf{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu \\ & - g_\sigma\bar{\psi}\sigma\psi - g_\omega\bar{\psi}\gamma_\mu\omega^\mu\psi - g_\rho\bar{\psi}\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\rho}^\mu\psi - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4, \end{aligned} \quad (1)$$

$$\Omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \quad \mathbf{R}_{\mu\nu} = \partial_\mu \boldsymbol{\rho}_\nu - \partial_\nu \boldsymbol{\rho}_\mu. \quad (2)$$

Here ψ is the nucleon field, σ stands for σ -boson field, ω for ω -meson field and ρ for ρ -meson field. Non-linear self-coupling terms for σ -boson, which are crucial for a realistic description of nuclear properties within Relativistic Mean Field Theory (RMFT), are also included. Deriving the particle-particle (p-p) channel interaction in the relativistic models is one of the current topics though practical approach, namely, the use of a non-relativistic force (*e.g.* Gogny force) in p-p channel, has been adopted in the finite nuclei calculations.

The first study of pairing by means of QHD was done by Kucharek and Ring in 1991.² In order to incorporate the pairing field, meson fields must be quantized and the anomalous Green's function is defined by the Gor'kov factorization. The customary manipulation gives Relativistic-Hartree-Bogoliubov (RHB) equation. Hence a transcendental equation of effective nucleon mass for the mean field and an ordinary non-linear gap equation for the pairing field organize the non-linear system of equations.

The resulting gap obtained by adopting the one-boson-exchange (OBE) interaction with RMFT parameter set such as NL1 is too large to achieve a consensus. Aforementioned “practical approach” for finite nuclei is a remedy for this excessive gap problem. In nuclear matter, alternatively, a realistic force can be used as p-p interaction and produces a consistent result with the non-relativistic studies, where the maximum pairing gap ranges from 2-4 MeV.³

A possible extension in alignment with the above policy is to take the change of the hadron properties into consideration. In the pioneering work done by Brown and Rho, it was pointed out that the change of hadron masses may occur in conformity with the chiral symmetry arguments.⁴ Although there is still controversy on this subject, some experiments seem to support the vector meson mass decrease. The change is expressed by the linear relation between the masses and the density:

$$\frac{M^*}{M} = \frac{m_{\rho,\omega}^*}{m_{\rho,\omega}} = \frac{\Lambda_{\rho,\omega}^*}{\Lambda_{\rho,\omega}} = 1 - C \frac{\rho}{\rho_0}, \quad C = 0.15, \quad (3)$$

where M is the nucleon mass, $m_{\rho,\omega}$ are the masses of the ρ - and ω -meson and $\Lambda_{\rho,\omega}$ are the cutoff masses in the form factors applied to each nucleon-meson vertex. The scaling factor C is taken to be 0.15, which is almost in line with

the one obtained from QCD sum rules. This relation is often referred to as “Brown-Rho (BR) scaling.”

Then, Rapp *et al.* showed that hadron mass decrease conforming to this scaling was compatible with the saturation property of nuclear matter.⁵ They constructed the OBE potential just by adding two extra σ -bosons to the original Bonn-B potential with slightly modified parameters. This “In-Medium Bonn potential” makes the investigation of the medium effects on superfluidity quite tractable. Accordingly we adopt this potential as the p-p interaction in the gap equation.

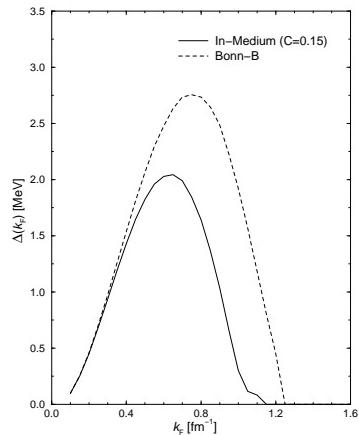


Figure 1: The pairing gaps at the Fermi surface as a function of Fermi momentum k_F . Details are in the text.

The resulting pairing gap at the Fermi surface is shown in Figure 1, which is drawn as a function of Fermi momentum with the solid line. The dashed line corresponds to the gap obtained by using the original Bonn-B potential. Comparison shows that the inclusion of hadron mass decrease in concert with BR scaling reduces the gap significantly, however, the values stay in the physically acceptable range.

Before going into the detailed discussion of the gap, the structure of the gap equation has to be reviewed to clarify how the contributions come from each momentum region. As pointed out by Rummel and Ring,³ on the one hand, positive contributions come from the low- and high-momentum region where the gap has the opposite sign to the potential, which is due to the minus sign in the integrand of the gap equation. On the other hand, negative contributions come from the intermediate-momentum region where the both potentials have a repulsive peak.

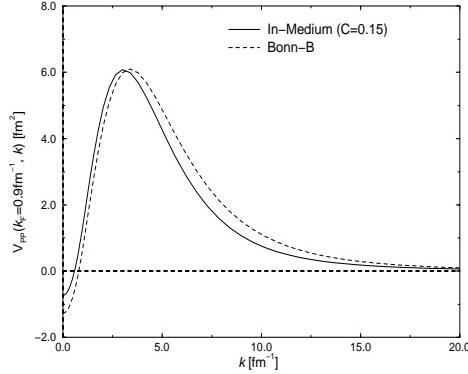


Figure 2: The particle-particle channel interactions as a function of momentum, with a Fermi momentum $k_F = 0.9 \text{ fm}^{-1}$. Details are in the text.

Next, to see the mass decrease effects on the p-p interaction, In-Medium Bonn potential and the original Bonn-B potential are given in Figure 2, which represents the shift of the In-Medium Bonn potential to the lower-momentum region. In other words, the hadron mass decrease leads to reduction of magnitude in the region giving the positive contributions to the gap as mentioned above. This is the main reason why reduction of the gap occurs in the case of In-Medium Bonn potential.

But a question may arise: which hadron is responsible for this reduction, nucleon or meson? In order to answer this, we also calculate the gap applying BR scaling only to either hadron. The result is shown in Figure 3, where the solid, dashed and long-dashed line correspond to the case of decreasing only the nucleon mass, only the meson masses and the both, respectively. This figure ascertains that the reduction of the gap is mainly due to the meson mass decrease though the nucleon is responsible for it to some extent.

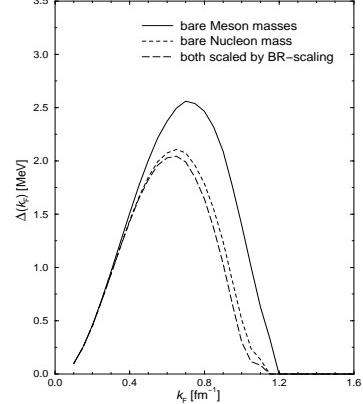


Figure 3: The pairing gaps obtained with the partially BR scaled p-p interactions. Details are in the text.

In summary, we performed the numerical calculation of the pairing gap using In-Medium Bonn potential as the p-p interaction. The resulting gap is considerably reduced in comparison with the one obtained with the original Bonn-B potential and is consistent with the non-relativistic studies. The use of the meson theoretic potential reveals that the vector meson mass decrease, or lengthening the range of repulsive forces accounts for the reduction. Whether the polarization of Dirac sea as well as Fermi sea is effective for it remains a conjecture left for further investigation.⁶

References

- [1] B. D. Serot and J. D. Walecka, *Adv. Nucl. Phys.* **16**, 1 (1986).
- [2] H. Kucharek and P. Ring, *Z. Phys. A* **339**, 23 (1991).
- [3] A. Rummel and P. Ring, *preprint* (1996).
- [4] G. E. Brown and M. Rho, *Phys. Rev. Lett.* **66**, 2720 (1991).
- [5] R. Rapp *et al.*, *LANL e-Print archive* nucl-th/9706006.
- [6] M. Matsuzaki and P. Ring, *ibid.* nucl-th/9712060; M. Matsuzaki, *Phys.*

Rev. C **58**, 3407 (1998).